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DIE-BACK OF CONTAINER-GROWN DOUGLAS-FIR SEEDLINGS: ASSOCIATED MICROCLIMATE

BY

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ABSTRACT

Microclimatic conditions associated with Douglas-fir needle-tip die-back were investigated in two container greenhouses operated by Canadian International Paper Inc. in Saanichton, B.C. Emphasis was on maximum soil temperature in different types of growing media. The effects on soil temperature of two kinds of grit cover were also examined. The lack of significant levels of needle-tip die-back prevented any direct associations to be made between microclimate and the disease. However, the soil temperature environment was described and a relationship between ambient and soil temperature was determined. Mean greenhouse (all treatment) soil temperatures, lagged 15 minutes behind ambient, could be described by the regression equation: Soil temperature = 1.4 x ambient temperature - 5.8°C.

The greatest significant differences between soil formulation temperatures occurred in mixes comprised of different peat types. The physical difference between these peats was mainly in the speed with which they absorb water. New Langley peat, with the lowest hydraulic conductivity, also had temperatures most significantly lower than the Manitoba peat. Soil temperatures were higher in a fibreglass-covered greenhouse than in a polyethylene-covered greenhouse. Different watering regimes may have contributed to this. Soil temperatures were higher than ambient for about 18-20 hours per day.

Grit cover can significantly alter soil temperature. Higher soil temperatures and a greater frequency of high temperatures were observed under dark-coloured Forest sand than under light-coloured Granite grit.

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INTRODUCTION

Successful establishment of newly germinated conifer seedlings is dependent on their survival past a critical succulent stage. This period of growth begins when the seedling appears above the soil surface and lasts until the hypocotyl has become hard and wiry. During this time, heat is the most important limiting factor to growth. Most seedlings die from high transpirational stress and drought on hot seedbeds (Arnott 1973).

The thermal death point of most conifer seedlings is reached with internal tissue temperatures about 54°C (Baker 1929, 1950; Roeser 1932; Seidel 1986; Shirley 1936). Baker (1929) found that of all injuries occurring below tissue temperatures of 54°C, the majority occurred in young seedlings with cotyledons barely out of the seed coats.

Although all species may die at the same tissue temperature, they differ in their capacity to maintain temperatures in the hypocotyl that are lower than surface soil temperature.

Shirley (1936) states the cooling effect of transpiration to be the most important factor involved in plant resistance to heat in dry air. Clum (1926a), however, presents the alternative view that leaf temperature is more dependent upon the intensity of incident solar radiation than on transpiration rate. Clum (1926b) suggested the thermal death point of most plants to be about 50°C and that only under extreme conditions, when leaves are heated somewhat above their thermal death point, will the small effects of transpiration be critical in protecting them.

Baker (1929) found little evidence that internal stem temperature was held down by the transpiration stream. However, because rapid changes in

the amount of conducting tissue occurs in seedlings during the succulent stage, he pointed out that a few days can make a considerable difference in a seedling's ability to tolerate high temperatures. Isaac (1938) found surface soil temperatures of 50°C for several days following germination of Douglas-fir seedlings were enough to injure, while several days of 51°C were enough to kill. Baker (1929) concluded that damage to seedlings may appear at surface soil temperatures as low as 47°C. It becomes general when 53°C is exceeded and severe at temperatures greater than 65°C. He found the internal stem temperature of Douglas-fir seedlings to be 8-11°C lower than surface soil temperature.

The effect of high soil temperatures on nutrient uptake, transpiration and photosynthesis, and soil water viscosity can directly impact on seedling survival at the succulent stage (Babalola et al. 1968; Baker 1950; Havranek 1972). At high soil temperatures, the ability of Monterey pine seedlings to transpire was lost more rapidly as soil water suction increased than at low soil temperatures (Babalola et al. 1968). Transpiration and photosynthesis in Larix decidua and Picea abies both increased with higher soil temperature (Havranek 1972). Relatively few data are available concerning water absorption at high soil temperatures. Usually only those roots in surface soil, in greenhouse benches or containers are subjected to temperatures high enough to interfere with water absorption (Kramer and Duke 1969). Kaufman (1976) reports increased transpiration rates in Engelmann spruce with increased soil temperature. Flow resistance and viscosity of water decreased proportionately as soil temperature increased. He cautions, however, that drying cycles associated with high soil temperatures can decrease water absorption by effecting a reduction in

the amount of root contact with the soil. Observations (unpublished) of root diameter were made during a study of water stress effects on pine seedlings (Kaufman 1975). Roots of seedlings subjected to drying cycles became suberized, the cortex collapsed and their diameter decreased by 50-60%. Significantly higher root resistances to water absorption were calculated to exist during a second drying cycle than the first (Kaufman 1976).

Exterior soil and ambient temperatures associated with plant physiology and pathology have been documented; however, these conditions in forest nursery container greenhouses have not been extensively examined. In many instances it is not possible to extrapolate outside conditions to the greenhouse where soil temperatures are often higher than those of the air above. Also, greenhouse air temperature is usually higher than that outside. A study of soil temperature in a plastic greenhouse and an open nursery showed higher daily maximum and minimum air temperatures in the greenhouse (Leikola 1976). Inside the greenhouse, the cumulative soil temperatures at 1 cm, 5 cm and 10 cm depths were higher than the cumulative air temperature. Outside in open peat seedbeds, the opposite was found. In a study of outside site conditions affecting the establishment of Douglas-fir seedlings in the field, soil temperatures at depths of 7.6 cm, 15 cm and 30.5 cm with the surface exposed to full sunlight, were always below the ambient air temperature (Isaac 1938).

Solar radiation strikes the earth's surface and is either absorbed or reflected. The absorbed solar radiation combined with absorbed long wave radiation from the surrounding environment warms the ground surface. The

surface itself emits longwave radiation proportional to its surface temperature. The difference between the absorbed and emitted radiation on a unit area per unit time is called the net radiation flux density (hereafter referred to as the net radiation). If the net radiation is positive (more energy received than emitted), the surface warms. If more radiation is emitted than absorbed, the surface cools via net radiation. Three other heat transfer processes take place at the ground surface. Some heat is used to evaporate water and returns to the atmosphere as latent heat of the water vapour. Some heat is directly exchanged with the atmosphere via convection. This process cools a surface that is warmer than the overlying air but warms a surface that is cooler than the air. Finally, heat flux density takes place between the surface and deeper soil layers through conduction. The net balance of all these heat transfer processes combined with the heat capacity of the soil determines the temperature of the soil surface. Heat flux density into and out of the soil, combined with the soil's heat capacity, control the temperature of deeper soil layers (soil temperature).

In addition, water added to a soil via precipitation or overhead irrigation may warm or cool the soil if its temperature differs from that of the soil. In most cases the temperature of added water would be less than the mid-day soil temperatures observed in this study.

In conifer seedling container nurseries, soil refers to the growing medium in styrofoam containers. A 313 styroblock measures 0.36 m x 0.60 m x 0.15 m and contains 160 cavities, each holding a maximum of 10 cm^3 of media. Each styroblock occupies a volume of 0.032 m^3. Five percent of

this total volume consists of the growing medium. The containers are usually supported above the ground on benches.

As well as shortwave solar radiation incident on the styroblock, soil in the container greenhouse is heated by longwave energy emitted and reflected from the floor and other structures. Also, heat is conducted between blocks and from the bench surfaces. Finally, rising ambient air temperature during the day contributes significantly to warming of the styroblocks and the soil within them through convection. The difference in heat transfer processes between the styroblock container raised above the floor in the confined volume of a greenhouse, and exterior soil exposed to wind and open sky, renders the estimation of container soil temperature from outside conditions invalid.

A phenomenon in container nurseries recently associated with high soil temperatures is Douglas-fir needle-tip die-back. During the 1984 and 1985 growing season, approximately 20% of the Douglas-fir seedlings at the Canadian International Paper (CIP) container nursery in Saanichton, B.C. exhibited die-back symptoms. The die-back occurs in patches throughout the Douglas-fir seedlots. Each patch expands from a few infected seedlings in the first two weeks after germination to 10-20 seedlings during the next two months. Losses have occurred in British Columbia Ministry of Forests and Lands (BCMOFL) and private nurseries during the past five years (Husted 1985). The main species affected in all nurseries is Douglas-fir.

Die-back symptoms are first noticed when the seedlings are 1-2 cm tall. They include stunting, twisting and wilting of the shoot tips concurrent with die-back of the needles from the tips to the stems. Seedling roots appear finer and more suberized than normal.

The causal agent(s) of die-back are unknown; however, high ambient and media temperatures during germination appear to increase the incidence of die-back in Douglas-fir seedlings. Observations made by CIP personnel in 1985 found high temperatures to be associated with needle-tip die-back (Husted 1985). The severity of die-back generally increased when daily maximum temperatures were high during germination. The use of Forest sand instead of Granite grit for a media grit cover in 1985 likely contributed to high container soil temperatures. Forest sand is darker in colour as well as less angular in shape than Granite grit. On July 15, 1985 temperatures immediately below the Forest sand and Granite grit reached 40°C and 33°C, respectively. CIP personnel felt that media temperatures during germination and early seedling growth exceeded 30°C, the limit a 1983 silviculture memo cautions should not be exceeded (Husted 1985).

High temperatures associated with Douglas-fir needle-tip die-back at the CIP container nursery in 1985 likely had several effects on the seedlings and media. Transpiration and photosynthetic rates may have been influenced. The release of Osmocote and the availability of micronutrients or concentrations of toxins may have been altered by high temperature. Because root tissue is more susceptible to heat damage than shoot tissue, the probability of root diseases or decreased water absorption may have been increased.

Conifer seedlings are susceptible to heat damage during the succulent growth stage, and Douglas-fir needle-tip die-back during this period seems to be associated with high air and media soil temperatures. Thus, an investigation was made of media temperatures in styroblock containers and the ambient atmospheric environment above them. Emphasis is on maximum

temperature. The study paralleled CIP research investigating nutrient imbalance in the media, poor media aeration, media bulk density and media mix combinations. No detailed information was available on the temperature pattern of container growing media. Observations were made during three growth trials to determine diurnal patterns of ambient and media temperatures as well as relationships between the two. Differences between media temperatures in various mix formulations were determined as were those between media under Forest sand and Granite grit covers.

MATERIALS AND METHODS

Observations for three trials were recorded inside two greenhouses at the CIP nursery in Saanichton, B.C. Trial 1 was conducted in a polyethylene (HOOP) greenhouse from March 27 to May 14, 1986. Physical properties and soil temperatures were examined for 12 soil mix formulations used as part of CIP's die-back investigation. Each mix is categorized in terms of three factors: 1) peat source, 2) additives (vermiculite, perlite or none) and 3) presence or absence of slow-release fertilizer (Osmocote) (Table 1). Media was mixed and styroblocks filled as per standard CIP production procedure. The ratio of peat to additive in a mix was 2/1. For treatments with slow-release fertilizer added, the average number of prills per cavity was 10. Block watering in all three trials followed CIP's normal schedule to keep the soil moist.

Treatment styroblocks were randomized in the greenhouse on benches 1 m above the floor. One styroblock from each treatment was randomly selected for measurement. Within that block, a randomly selected cavity was instrumented to measure soil (medium) temperature (Figure 1). Radiation and ambient air temperature and humidity were recorded near the centre of each trial site (Figure 1).

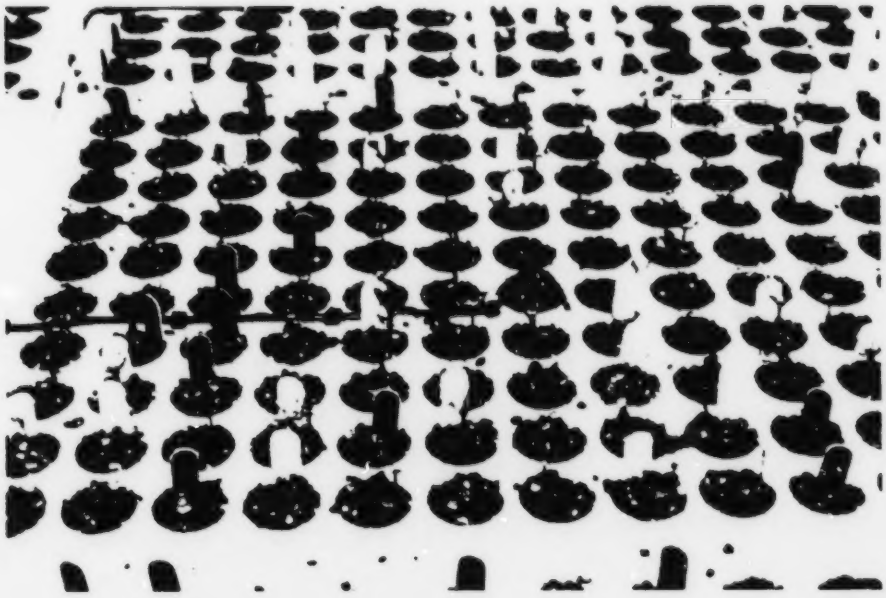
Media temperatures in all three trials were measured using thermocouples (copper-constantan) buried 5 cm beneath the soil surface. Ambient conditions were measured 20 cm above the block surface using temperature and humidity sensors (model PL2-200, Micromet Systems, Vancouver, B.C.). All data were recorded every 15 minutes on microprocessor-based data loggers (model 21X, Campbell Scientific, Edmonton, Alberta). Trial 1 solar

Table 1. Soil mix formulations.

MIX NUMBER	FACTOR 1 PEAT SOURCE	FACTOR 2 ADDITIVES	FACTOR 3 FERTILIZER
1	Old Langley*	None	None
2	Old Langley	Vermiculite	None
3	Old Langley*	Vermiculite	Osmocote
4	Old Langley	Perlite	None
5	New Langley	None	None
6	New Langley	Vermiculite	None
7	New Langley*	Vermiculite	Osmocote
8	New Langley	Perlite	None
9	Manitoba	None	None
10	Manitoba	Vermiculite	None
11	Manitoba*	Vermiculite	Osmocote
12	Manitoba	Perlite	None

* Omitted from Trial 2

A.



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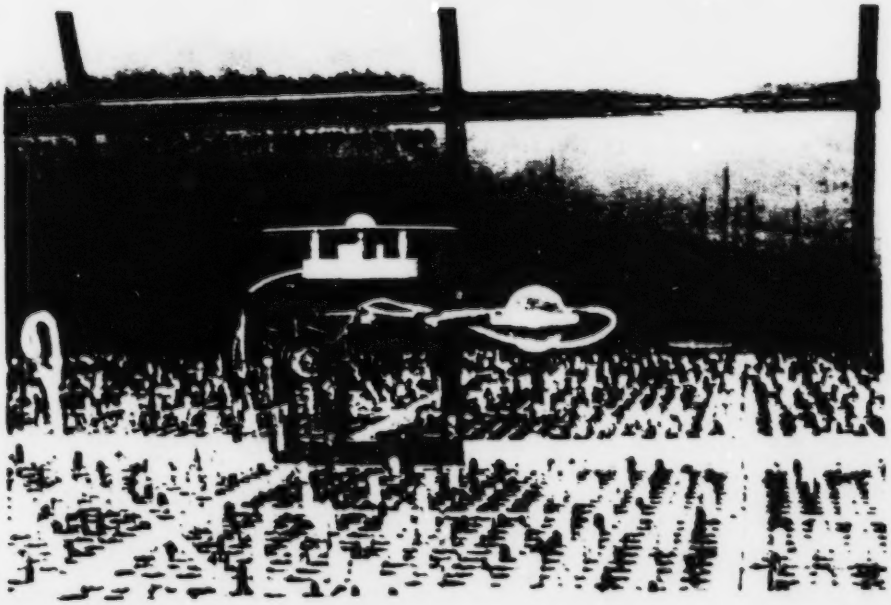


Figure 1. Randomly selected cavity within a styroblock showing thermocouple location (A) and radiation and ambient sensors near the centre of a trial site (B).

radiation was sensed with a pyranometer (model Solarimeter CM5, Kipp and Zonen, Delft, Holland). Net radiation was determined using a net pyradiometer (model CN1, Synchrotac Middleton Instruments, Mulgrave, Australia).

Trial 2 environmental parameters were recorded from May 21 to July 3. Measurements were taken in the HOOP greenhouse as well as a fibreglass-covered (MAIN) greenhouse. Soil mixes containing Osmocote and Old Langley peat with no additives were omitted, reducing the number of Trial 2 formulations to eight in each greenhouse. Equipment constraints made this reduction necessary.

Soil and ambient conditions were measured and recorded as in Trial 1. In the HOOP greenhouse, solar and net radiation were measured as in Trial 1. In the MAIN house, solar radiation was measured with a silicon cell pyranometer (model LI-200S, Li-Cor Inc., Lincoln, Nebraska). Net radiation was measured using a net pyradiometer (model S-1, Swissteco Pty. Ltd., Melbourne, Australia). Prior to Trial 2, the silicon cell pyranometers and the Kipp and Zonen Solarimeter were calibrated against each other. The same procedure was used to calibrate the Synchrotac Middleton and the Swissteco net pyradiometers to each other.

A third trial to investigate the effect of grit cover type on media temperature was conducted from July 15 to August 28. A CIP production media consisting of a 2/1 New Langley peat/vermiculite mix was used. No fertilizer was added. Half of the media examined were covered with Forest sand, a commercial soil cover consisting of dark coloured, smooth sand grains, each averaging 3 mm in diameter. The other mix was covered with Granite grit. This cover is made of sharp, angular grains of crushed

granite, each averaging 3 mm across at the widest point. The Granite grit is light grey, almost white, in colour.

Eighteen, 313 styroblocks were filled with soil mix. These were arranged on benches 1 m above the floor in the MAIN greenhouse so that nine blocks covered with Forest sand were beside the other nine covered with Granite grit. Seven randomly selected cavities in the centre styroblock of each group of nine were instrumented to measure soil temperature at a depth of 5 cm (Figure 2). Ambient conditions were recorded beside the experiment site and separate radiation measurements were made above each group of treatment blocks.

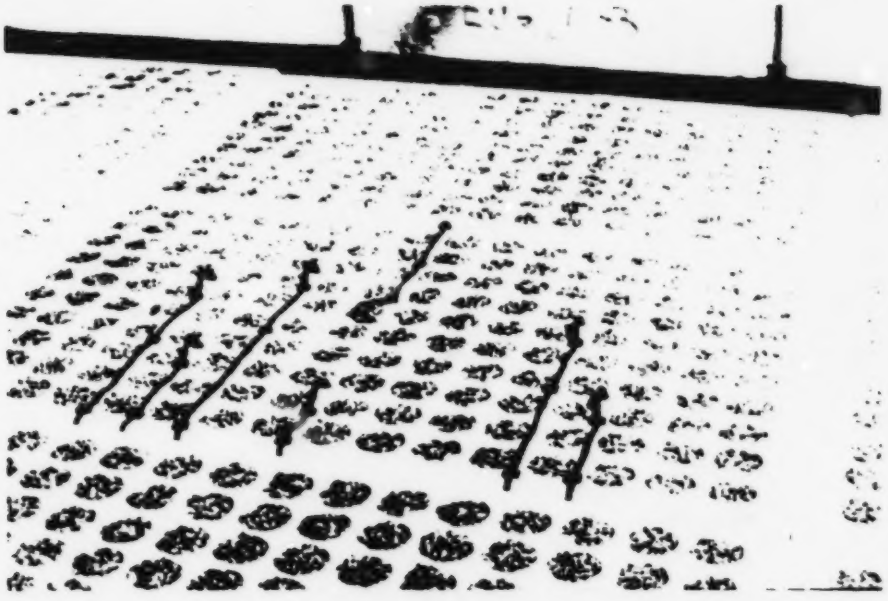
Media temperatures, ambient conditions and incoming solar radiation were measured and recorded as in Trial 1. Net radiation was measured over the Forest sand using the Middleton net pyradiometer and over the Granite grit using the Swissteco net pyradiometer. Reflected shortwave radiation was measured over the two treatments using inverted silicon cell pyranometers (model LI-200S, Li-Cor Inc., Lincoln, Nebraska).

Physical properties of each soil mix were determined (Soilcon Laboratories Ltd., Vancouver, B.C.). Water retention data thus obtained were used in Campbell's equation (Campbell 1974) to determine the hydraulic conductivity for those soil mix formulations showing significantly different maximum temperatures.

Retrieved climatic data were initially edited and compiled using a Compaq microcomputer. Statistical analysis was performed on an IBM 3083 BX mainframe computer. The Newman-Keuls multiple range test was applied to ranked sample means (12:00-17:00) of maximum soil temperatures for each media mix formulation (Zar 1984). For differences between measured

parameters where multiple comparisons were not examined, paired-comparison t-tests were used. Forward, stepwise multiple regression analysis was used to regress lagged values of media temperature on ambient temperature and solar radiation. A final simple linear regression was made by regressing 15 minute lagged media temperature, on ambient temperature.

A.



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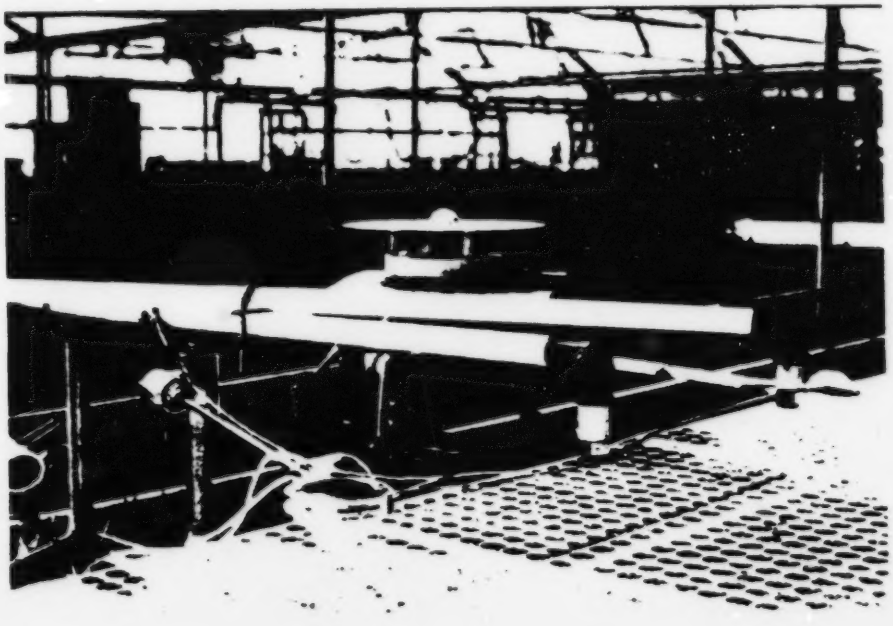

Figure 2. Thermocouple location in randomly selected cavities (A) and radiation and ambient sensor location (B) in the Grit trial. Photo (A) shows the Granite grit. Granite grit is in the foreground and Forest sand is in the background of (B).

RESULTS

The mean daily peak of solar radiation occurred between 13:00 and 14:00 in all trials. The mean daily peak values (the highest mean value of 96 observation times that occurred during the day) averaged over the trial were 438 watts/m^2 in the MAIN greenhouse and 386 watts/m^2 in the HOOP greenhouse during Trial 2. The mean daily peak value during the Grit trial was 454 watts/m^2. Absolute maxima (the highest single value recorded during a trial) were: 756 watts/m^2 in the MAIN greenhouse and 731 watts/m^2 in the HOOP greenhouse during Trial 2; and 568 watts/m^2 during the Grit trial. Trial 1 (HOOP greenhouse) absolute maximum was 70% of the HOOP greenhouse, Trial 2 value.

The overall daily mean solar radiation in Trial 2 was 10 watts/m^2 greater in the fibreglass MAIN greenhouse than in the polyethylene HOOP greenhouse ($P=0.05$, $df=54$). The mean daily maximum value (mean of the highest values recorded each day) was 18 watts/m^2 higher in the HOOP greenhouse however ($P=0.01$, $df=56$).

The albedo (the percentage of incident solar radiation that is reflected) of the styroblock surfaces in Trial 2 was about 52%.

Absolute maximum values of net radiation in Trial 2 were observed between 12:00-13:00, and reached 440 watts/m^2 in each greenhouse. Mean, daily peak net radiation values of 214 watts/m^2 and 175 watts/m^2 were observed in the HOOP and MAIN greenhouse respectively between 12:00-13:00.

Mean daily peak net radiation values of 220 watts/m^2 and 179 watts/m^2 were observed over the Forest sand and Granite grit respectively between 14:00-15:00. Absolute maximum net radiation reached 331 watts/m^2 over the

Forest sand and 288 watts/m^2 over the Granite grit. For all times, the mean daily net radiation over the Forest sand was 13 watts/m^2 greater than over the Granite grit (P=0.05, df=93). Maximum net radiation values were 11 watts/m^2 greater over the Forest sand than over the Granite grit (P=0.05, df=93).

The mean of the albedos recorded at the time of maximum incident solar radiation each day during the Grit trial were 58% for the Forest sand and 63% for the Granite grit. The difference between the two was 5% (P=0.001, df=53).

Diurnal patterns of absolute maximum ambient temperature (the single highest value observed at each hour over the length of the trial) and maximum, mean soil temperature (the highest single value, of the mean over the treatments, observed at a specific time over the length of the trial) are shown in Figures 3 and 4.

Maximum, mean soil temperature was higher than absolute ambient from early morning onward in all locations in each trial. The differences between the two temperatures were greatest in the Grit trial, Forest sand covered media for all times (Table 2) and in the HOOP house during Trial 2 for the hottest part of the day (12:00-17:00) (Table 3).

The frequency of maximum, mean soil temperatures above 37.5°C (computed on the basis of 96 observation times through the day, 1 observation every 15 minutes) was greatest in the MAIN greenhouse during Trial 2 (Figure 5). Although the greatest difference between soil and ambient temperatures occurred between 12:00-17:00 in the HOOP house during Trial 2, a greater frequency of high soil temperatures was observed in the MAIN greenhouse (Figure 6). The distribution of soil temperatures in the MAIN

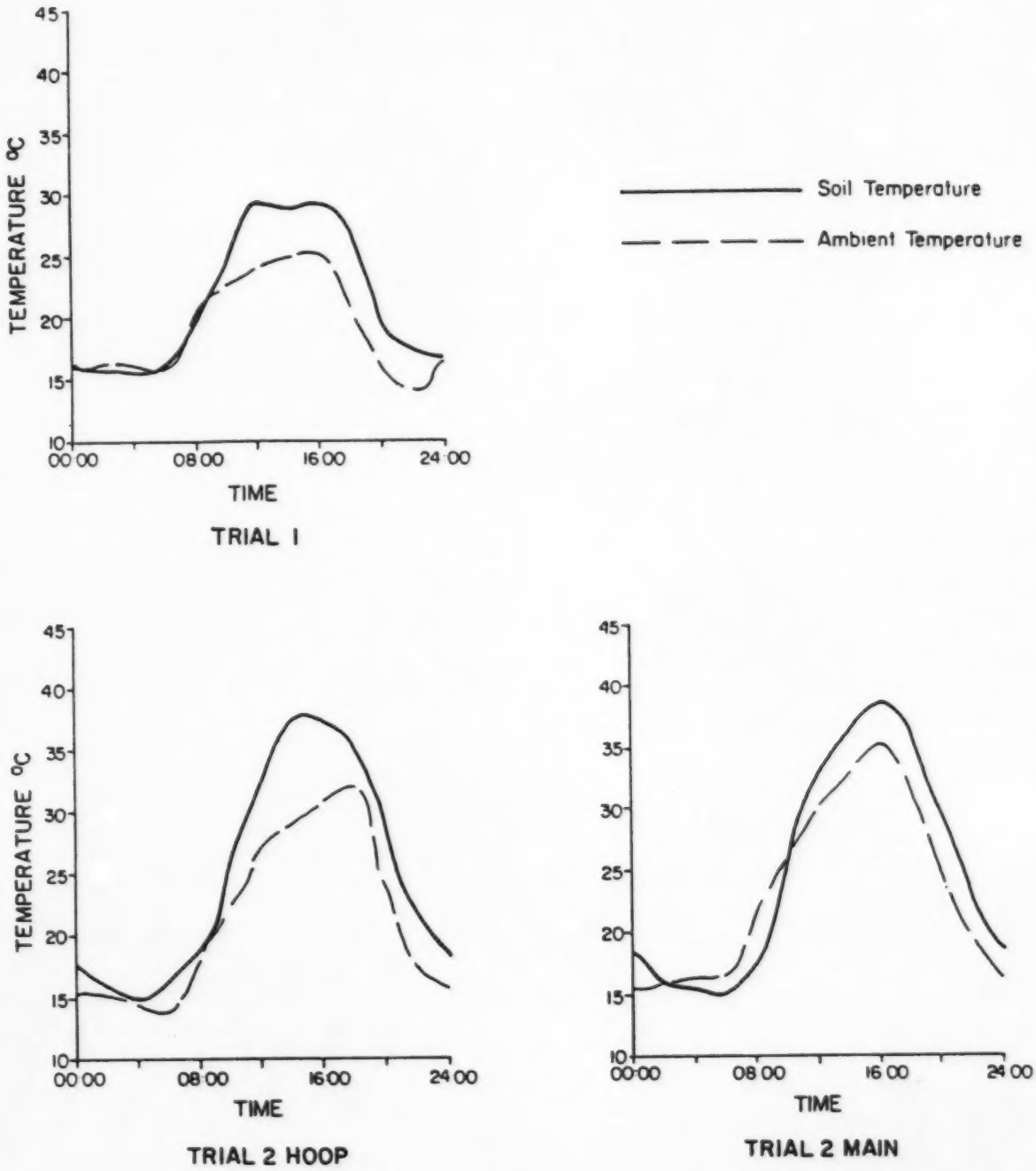

Figure 3. Diurnal patterns of maximum ambient and maximum, mean soil temperatures in Trial 1 in the HOOP greenhouse and Trial 2 in the HOOP and MAIN greenhouses.

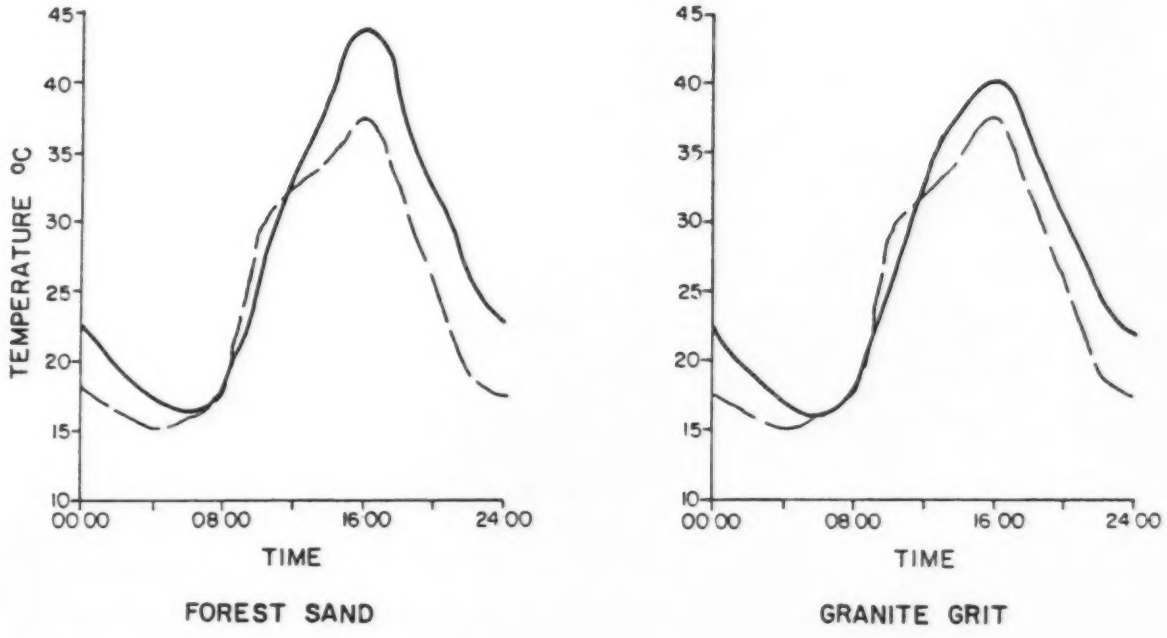

Figure 4. Diurnal patterns of maximum ambient and maximum, mean soil temperatures under Forest sand and Granite grit in the Grit trial.

Table 2. Differences between maximum, mean soil and maximum ambient temperatures (°C) at all times during Trial 1 in the HOOP greenhouse, Trial 2 in the HOOP and MAIN greenhouses, and during the Grit trial.

OBSERVATION	SOIL MINUS AMBIENT TEMPERATURE
Trial 1	0.8°C*
Trial 2 HOOP	3.2°C**
Trial 2 MAIN	1.8°C**
Grit trial, Forest sand	3.6°C**
Grit trial, Granite grit	2.1°C**

* P=0.001
** P=0.0001

Table 3. Differences between maximum, mean soil and maximum ambient temperatures (°C) from 12:00 - 17:00 during Trial 1 in the HOOP greenhouse, Trial 2 in the HOOP and MAIN greenhouses, and during the Grit trial.

OBSERVATION	SOIL MINUS AMBIENT TEMPERATURE
Trial 1	3.7°C*
Trial 2 HOOP	6.4°C*
Trial 2 MAIN	4.2°C*
Grit trial, Forest sand	5.4°C*
Grit trial, Granite grit	1.8°C*

* P=0.0001

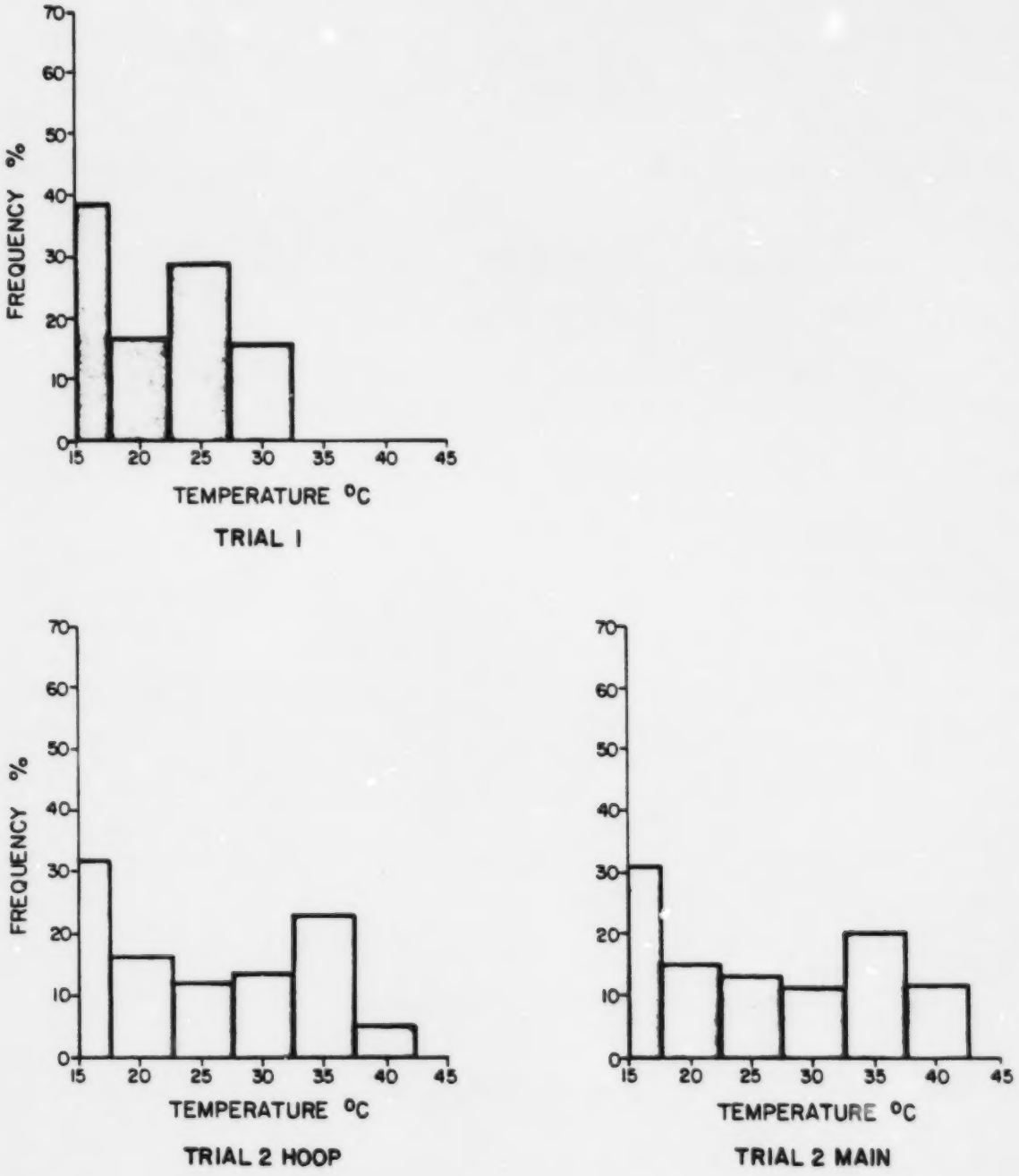

Figure 5. Frequency distributions of maximum, mean soil temperatures observed at all times in Trial 1 in the HOOP greenhouse and Trial 2 in the HOOP and MAIN greenhouses.

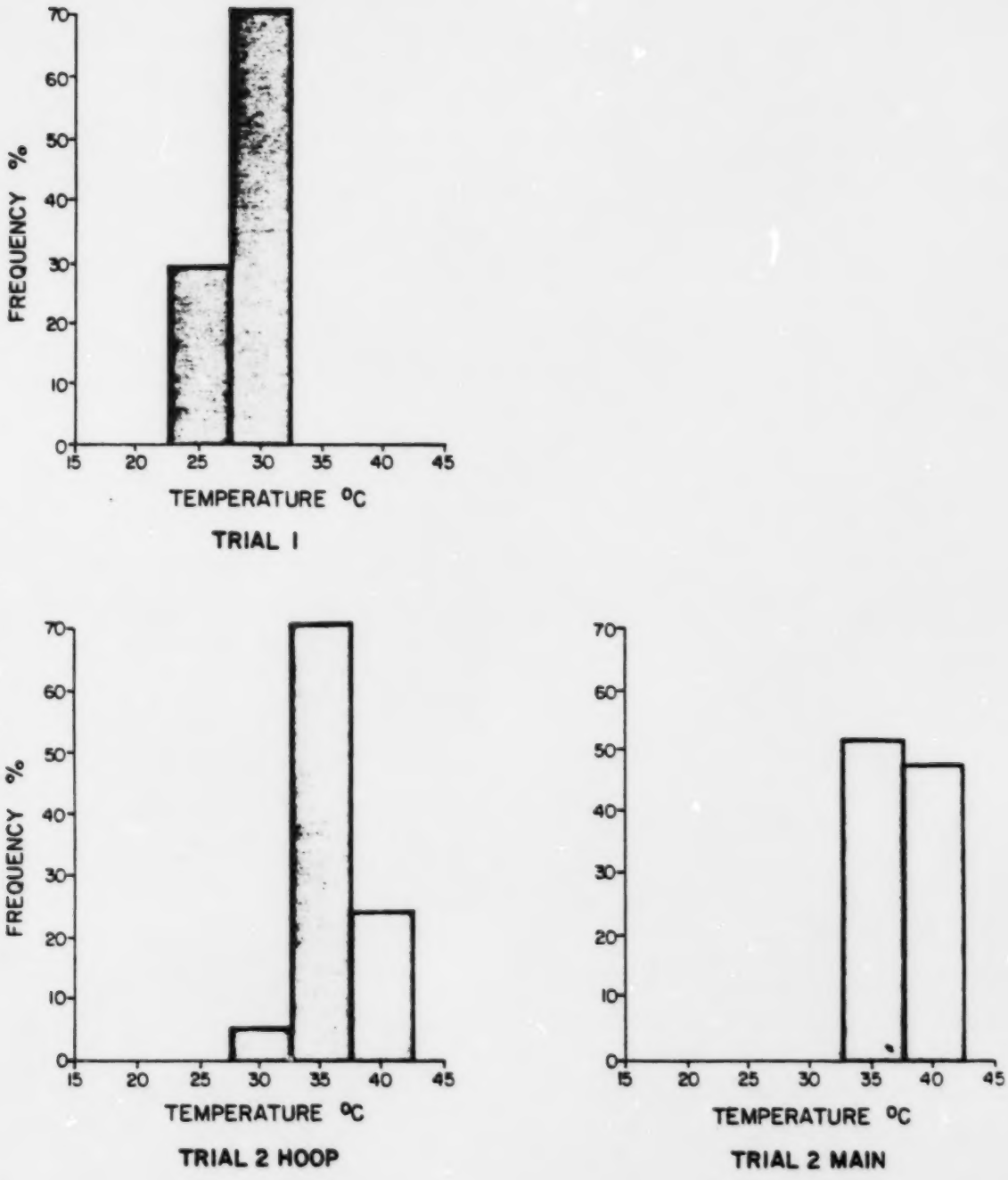

Figure 6. Frequency distributions of maximum, mean soil temperatures observed between 12:00 - 17:00 in Trial 1 in the HOOP greenhouse and Trial 2 in the HOOP and MAIN greenhouses.

greenhouse at these times was nearly evenly split between class intervals centered on 35 and 40°C. In the HOOP greenhouse between 12:00-17:00 during Trial 2, soil temperatures in the 35°C class interval occurred more than 70% of the time, with the distribution ranging from 27.5-42.5°C (Figure 6).

Soil temperatures encountered in the Grit trial were relatively evenly distributed between 12.5-47.5°C under the Forest sand. Thus, temperatures of 40°C or more at a depth of 5 cm are not uncommon in styroblock cavities during the succulent growth stage of seedlings. Nearly the same distribution of soil temperatures occurred under the Granite grit; however, temperatures encountered here only ranged from 12.5-42.5°C (Figure 7B). Between 12:00-17:00 in the same trial, maximum, mean soil temperatures in the 35°C class interval occurred more than 50% of the time under the Granite grit, with the remainder being below 42.5°C. Under the Forest sand during this same time, maximum, mean soil temperatures below 37.5°C occurred only 14% of the time. The remaining 86% of the soil temperatures were evenly distributed between the class intervals centred on 40 and 45°C (Figure 7C). The maximum, mean soil temperature between 12:00-17:00 in the Grit trial was 3.5°C higher in the Forest sand covered soil compared with Granite grit covered soil. This difference is significant at $P=0.0001$ (paired-comparison t-test, $df=17$).

The greatest significant difference in maximum soil temperatures between mixes involved Manitoba and New Langley peat. The Manitoba peat with no additives or fertilizer was 5.2°C warmer than the New Langley peat with nothing added in the HOOP greenhouse and 4.8°C warmer in the MAIN greenhouse during Trial 2 (Table 4). The soil temperature of Manitoba peat with vermiculite was 3.6°C higher than that of New Langley peat with no additives in Trial 1.

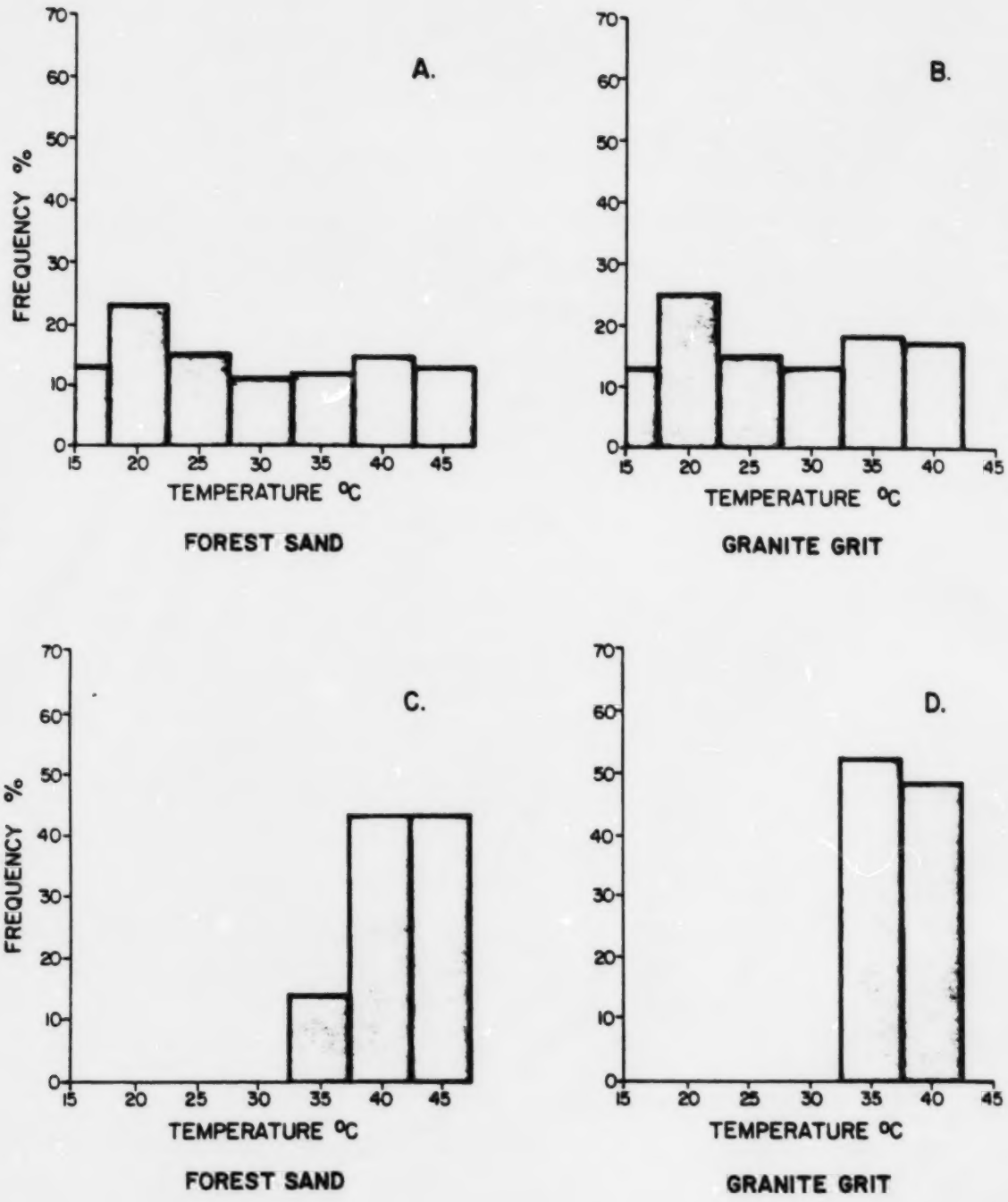

Figure 7. Frequency distributions of maximum, mean soil temperatures observed at all times under Forest sand (A) and Granite grit (B) and between 12:00 - 17:00 under Forest sand (C) and Granite grit (D) during the Grit trial.

Table 4. Newman-Keuls multiple range test results for differences between maximum soil temperatures observed between 12:00-17:00 in each soil mix formulation (treatments).

$$H_o: \mu_1 = \mu_2 = \mu_3 \ldots = \mu_k$$

$$H_a: \mu_1 \neq \mu_2 \neq \mu_3 \ldots \neq \mu_k$$

TRIAL	SIGNIFICANTLY* DIFFERENT TREATMENTS	DEGREES OF FREEDOM	DIFFERENCES BETWEEN TREATMENTS (°C)
Trial 1	10 > 5	11	3.6°C**
Trial 2 - HOOP	9 > 5	7	5.2°C**
Trial 2 - MAIN	9 > 5	7	4.8°C**

* See Table 1 for treatment formulas
** P=0.05

One of the controls of the difference in temperature between peat types could be their different moisture contents. Hydraulic conductivities of the New Langley and Manitoba peats with nothing added and the Manitoba peat with vermiculite are shown as functions of soil water content (Figure 8). For all three soil mixes, decreasing hydraulic conductivity coincides with decreasing soil water content. The New Langley peat that had significantly lower maximum soil temperatures between 12:00-17:00 also had higher hydraulic conductivities for given soil water contents than the other two soil mixes.

Regression analysis focused on the relationship of soil temperature with the more commonly measured air temperature. The best simple linear regression equation was obtained using Trial 2 data from the HOOP greenhouse. Regressing 15 minute lagged, mean (of the eight treatments) soil temperature on ambient temperature for daytime values between 05:00-17:00 (when the maximum effect of high temperature is expected), gave the regression equation:

$$MNSL = 1.4 \times AMBT - 5.8(^{\circ}C)$$

where MNSL = mean soil temperature and AMBT = ambient temperature 15 minutes earlier. For the equation, r^2 was 0.96 and the standard error of estimate was 0.039°C. Thus, during the day it is possible to estimate mean soil temperatures that will be reached in 15 minutes, as a function of the current ambient temperature.

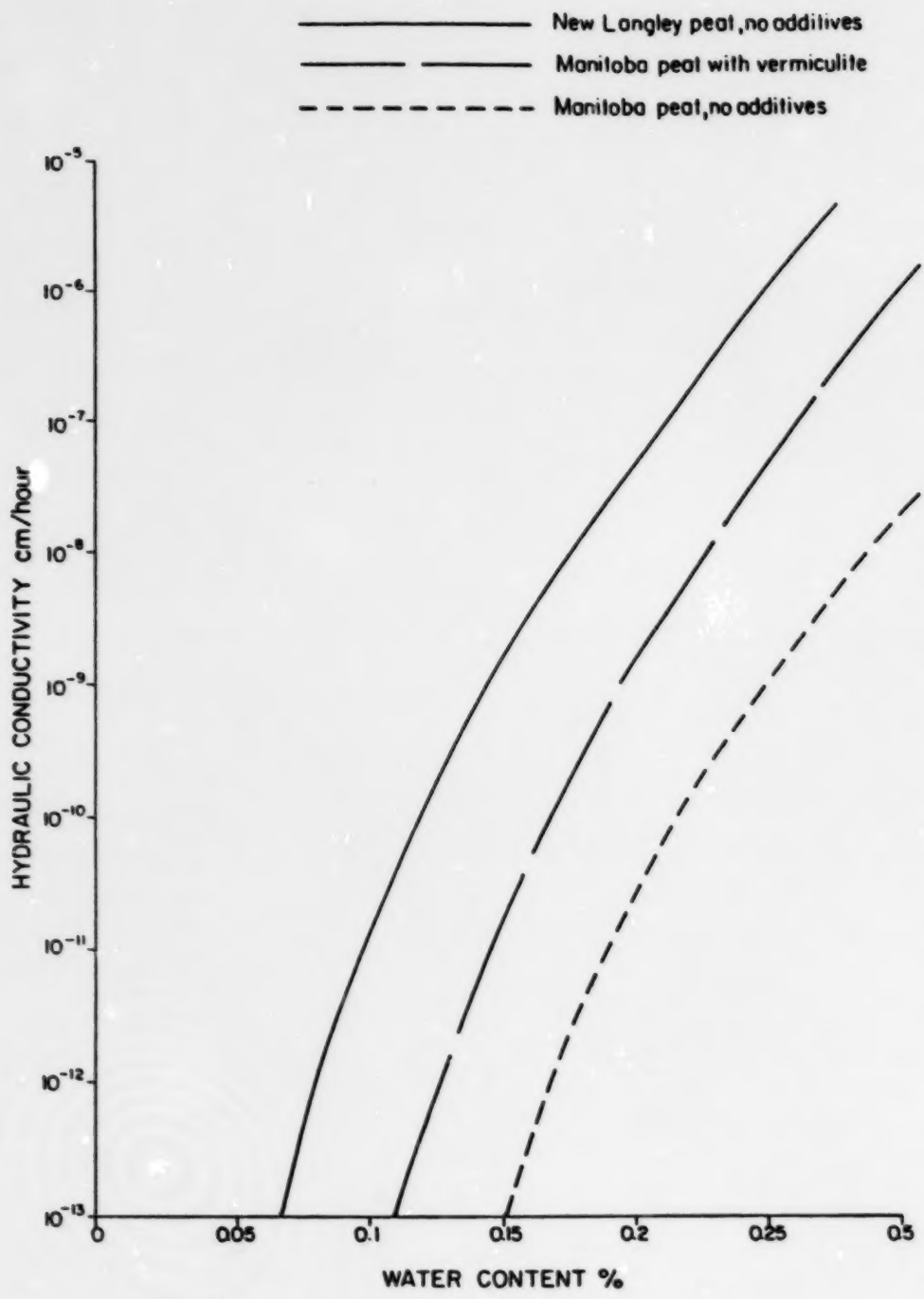

Figure 8. Hydraulic conductivity of New Langley and Manitoba peat with nothing added, and Manitoba peat with vermiculite, as functions of soil water content.

DISCUSSION

The energy source for ambient and soil heating in the greenhouse is solar radiation. Higher mean daily peak values of incoming solar radiation were detected in the MAIN greenhouse during Trial 2 than in the HOOP greenhouse. This was also true for absolute maximum values of solar radiation. The opposite would be expected due to the greater transmissivity of ultra-violet stabilized polyethylene covering the HOOP greenhouse than the fibreglass over the MAIN greenhouse (Walker and Slack 1970). Indeed, in an earlier study Peterson (1986) found a greater total of visible and near infrared radiation in the HOOP greenhouse than in the MAIN. Over the day, however, mean solar radiation in the MAIN greenhouse was only 10 watts/m^2 higher than in the HOOP greenhouse. Maximum values over the day were only 18 watts/m^2 greater in the HOOP greenhouse than the MAIN greenhouse.

The mean albedo of the styroblocks in each greenhouse was 52% during the day. This high albedo is expected because of the white color of the styroblocks. A high surface albedo is favourable for preventing high media temperatures but does contribute to the solar radiation heat load on the seedlings during the succulent growth stage.

Positive values of net radiation over the block surfaces during the day indicate the net amount of radiant energy absorbed by each styroblock from above. Longwave radiation losses from the bottom of the styroblocks were unaccounted for. Absolute maximum net radiation reached the same value in each greenhouse during Trial 2. However, mean daily peak net radiation was highest in the HOOP greenhouse compared to the MAIN. The observation site in the HOOP greenhouse was adjacent to a wall. Also, when

not in use, the superstructure of the overhead irrigation unit was near the observation site. Both the wall and irrigation unit may have contributed more incoming longwave radiation, helping to produce the higher midday net radiation values in the HOOP greenhouse during Trial 2. The MAIN house observation site was near the centre of the greenhouse with relatively little structural material to contribute to incoming longwave radiation. The irrigation unit in the HOOP greenhouse also may have intercepted diffuse beam solar radiation and been a factor in the lower solar radiation recorded in the HOOP greenhouse in this study. The net radiation values in each greenhouse could be described as moderate. The incident solar radiation is relatively high but the high surface albedo helps to limit the net radiation.

During the Grit trial, mean daily peak and absolute maximum net radiation were higher over the Forest sand than Granite grit. The lower albedo of the Forest sand (58%) than Granite grit (63%) contributed to higher net radiation values. The darker coloured Forest sand reflected less solar radiation than the light Granite grit despite the fact that more incoming shortwave radiation could be trapped within the sharp angular Granite grit due to multiple reflections.

The diurnal pattern of absolute maximum ambient and maximum, mean soil temperatures in each trial show how rapidly soil temperature overtook ambient once block heating began in the early morning (Figures 3 and 4). Although soil temperature rapidly became greater than ambient, it cooled off at about the same rate and did not drop below that of its surroundings until early the next morning. This rapid heating of the soil within the blocks in the greenhouses and subsequent rise above ambient was not

observed in outside peat beds by Leikola (1976). The small soil volume of each cavity heats rapidly, unlike outside beds where a greater proportion of the heat can be conducted to greater depths helping to limit the rise of temperature at any one depth (Cochran 1969). Once heated, soil within the styroblock cavities retains its heat due to the insulating qualities of the surrounding styroblock. Styrofoam has a very slow rate of heat transfer with a thermal conductivity of about 0.03 watts/m^2/K (Oke 1978). Saturated peat soil with an 80% pore space has a thermal conductivity of 0.5 watts/m^2/K, nearly 17 times greater (Oke 1978).

The greatest difference between maximum, mean soil and absolute maximum ambient temperatures over all times of the day occurred in the Grit trial (Table 2). Between 12:00-17:00 (afternoon period of highest daily temperatures), this difference was greatest during Trial 2 in the HOOP greenhouse (Table 3). The smallest difference between maximum, mean soil and absolute maximum ambient temperature between 12:00-17:00 occurred in the Grit trial under the Granite grit. Compared to Forest sand, the lighter coloured Granite grit with its higher albedo, effectively reduced the difference between maximum, mean soil and absolute maximum ambient temperatures during the afternoon.

Diurnal patterns of maximum, mean soil temperature in the two greenhouses during Trial 2 were similar (Figure 3). Frequency distributions, however, indicate a greater frequency of soil temperatures above 37.5°C in the MAIN greenhouse (Figure 5). The frequency of high soil temperatures in the MAIN greenhouse was even greater in the afternoon (Figure 6). Shortwave radiation in the MAIN greenhouse was significantly higher than in the HOOP greenhouse during Trial 2. No significant difference between maximum,

mean soil temperatures from 12:00-17:00 existed between greenhouses during Trial 2. This indicates the difference between incident solar radiation between greenhouses was of little practical importance with regard to soil temperature differences. This appears more logical when it is remembered that only about 50% of the solar radiation incident on the styroblocks is absorbed (Trial 2 albedo = 52%). The net radiation values were highest in the HOOP greenhouse during Trial 2 however, a condition that should have contributed to higher soil temperatures there. A likely explanation for the greater frequency of higher soil temperatures in the MAIN greenhouse centres around the watering regime there. Initially, watering in the MAIN greenhouse was not as frequent as in the HOOP greenhouse. Thus, blocks may have dried more, contributing to the higher temperatures. A linear relationship exists between volumetric heat capacity (quantity of heat required to raise 1 cm^3 1°C) and soil water content (Cochran 1969). The greater the soil water content, the more heat that must be applied for an increase in soil temperature. A 2.2°C temperature change to a soil with a moisture level of 30% will be a 6.7°C change to the same soil if dry (Cochran, 1969). In addition, the cooling effect of evaporation from the soil surface is reduced when the soil dries. Thus, the importance of maintaining adequate soil moisture levels to reduce the potential for frequent damaging high soil temperatures becomes clear. Isaac (1938) found that as the frequency of high temperatures increased, the temperature needed to cause damage to Douglas-fir seedlings was reduced below the normal thermal death point. Husted (1985) observed that rather than just high temperatures alone, frequency of high temperatures seemed to be associated with Douglas-fir needle-tip die-back.

High soil temperatures associated with low soil water volumes may also damage seedlings by their combined effects upon transpiration. Transpiration and photosynthesis both increase with higher soil temperatures (Havranek 1972). However, at high soil temperatures the ability of some seedlings to transpire is lost rapidly as soil water suction increases (Babalola et al. 1968). In the container greenhouse, Osmocote mixed with the soil releases fertilizer more readily as temperature increases. Correspondingly, soil water suction may increase as the osmotic pressure in the seedling roots increases relative to the surrounding soil. Any cooling of the seedling stem derived from increased transpiration flow at high temperatures may be suppressed because of increased soil water suction also associated with the temperature rise. Thus, a reduction in soil water content not only contributes to greater frequencies of high soil temperature, but may also impair the ability of seedlings to withstand the increased temperature stress.

Frequency distributions of maximum, mean soil temperatures encountered in the Grit trial emphasize the effect of surface material on high soil temperature (Figure 7). Between 12:00-17:00, 86% of the time, the highest mean soil temperatures recorded under the Forest sand were greater than 37.5°C. Half of this time, they were above 42.5°C. The lower albedo, and greater absorption of shortwave radiation by the Forest sand covered soil, was associated with an increased frequency of high temperatures. The potential for damage to seedlings at the succulent stage grown under a Forest sand cover clearly exists. Baker (1929) noted that damage to seedlings may appear at surface soil temperatures as low as 47°C. These temperatures were frequently approached 5 cm under the Forest sand while

not at all at this depth under the Granite grit. Although not measured, surface temperatures were likely in excess of 47°C.

Significant temperature differences between soil mix formulations were noted for each trial. The greatest differences appear to be between mixes of two different peat types. Manitoba peat mix with nothing added reached higher maximum temperatures between 12:00-17:00 during Trial 2 than did New Langley peat. In the first trial, Manitoba peat with vermiculite added reached higher temperatures than New Langley peat. Reasons for the observed differences may be linked to the physical properties of each peat and their abilities to rehydrate following a drying cycle. Figure 8 shows that for a given water content, a greater hydraulic conductivity exists for New Langley than for Manitoba peat. Hydraulic conductivity indicates the ability of a soil to rehydrate. Because New Langley peat is able to absorb water at a faster rate, it rehydrates more rapidly following a drying cycle and shows a greater frequency of lower soil temperatures. The addition of vermiculite to Manitoba peat coincides with an increase in hydraulic conductivity (Figure 8) and a decrease in soil temperature. However, no significant reduction in soil temperature was observed with the addition of vermiculite to New Langley peat. Thus, no universal effect of soil additives on soil temperature was found.

The rapid daily rise in soil temperatures above those of ambient (Figures 3 and 4) is further emphasized by examining the linear relationship between mean all-treatment soil and ambient temperatures. Soil temperature can be viewed primarily as a response to heat conduction between the surface and the depth of measurement. Because air temperature responds more quickly to a change in surface temperature than does soil

temperature, values of soil temperature would be expected to lag somewhat behind air temperature. A correlation analysis showed that soil temperature correlated most highly with ambient temperature measured 15 minutes earlier. Thus, the soil temperature lagged 15 minutes behind the air temperature. The best-fit regression equation was also obtained with soil temperature lagged 15 minutes behind ambient. The regression equation MNSL = 1.4 x AMBT - 5.8(°C) suggests that in the ambient (air) temperature range of 30-40°C the soil temperature at 5 cm will be about 23% greater than the air temperature. Styroblock soil temperatures are not commonly measured but air temperature is widely measured 20 cm above the styroblock surface in a Stevenson screen. In the absence of other information, multiplying the ambient air temperature, taken from a Stevenson screen on the bench, by 1.25 will provide an estimate of the 5 cm temperature the styroblock soil will reach in 15 minutes. This rule-of-thumb errs slightly on the high side, offering a margin of safety for protecting seedlings from high soil temperatures.

CONCLUSIONS AND RECOMMENDATIONS

In container greenhouses during the succulent growth stage of conifer seedlings, soil temperatures rapidly rise above ambient temperature early in the day. The insulating quality of styrofoam helps preserve soil temperature at values higher than ambient. The result is that soil temperatures are above ambient air temperature for 18-20 hours per day. This study has found that very high soil temperatures can occur in greenhouse containers under standard management practice (Appendices I and II). High soil temperatures reached in the container greenhouse may contribute significantly to seedling mortality brought about by phenomena such as Douglas-fir needle-tip die-back. High soil temperatures and subsequent lethal tissue temperatures may kill seedlings outright. In addition, constraints of increased soil water suction upon a seedling's ability to transpire may be induced by the same high temperatures that increased transpiration flow is needed to offset. Results of this research suggest that control of high soil temperatures in container greenhouses may be achieved by the choice of peat, maintaining adequate moisture levels within containers and by using an appropriate grit cover.

Recommendations to greenhouse growers to reduce the risk of high soil temperature damage to conifer seedlings include:

- Use a peat with good water absorption and retention characteristics;
- Maintain moisture levels in containers as high as possible to reduce the risk of extreme soil temperatures while still minimizing the risk of encouraging damping-off fungi;

- Avoid using a grit cover that is dark in colour. Lighter granite-type grit will reflect more incoming solar radiation, thus promoting a lower soil temperature.
- Use of the equation: Soil temperature = 1.4 x ambient - 5.8(°C) provides an estimate of the soil temperature likely to be reached within 15 minutes. The rule-of-thumb: soil temperature = 1.25 ambient temperature, may also be used within the 30-40°C air temperature range. If excessively high temperatures are predicted, compensating measures such as watering or using shade cloth should be immediately implemented where possible.

The lack of significant levels of Douglas-fir needle-tip die-back in any of the observational trials demands further work in order to definitively associate microclimatic conditions with this phenomena. However, other areas for future study have been suggested by this investigation. These include:

- Estimation of temperature profiles within styroblock cavities to establish thermal conductivities of soil mixes at different water contents;
- Determination of radiant surface temperatures of grit covers under different ambient conditions. Stem lesions caused by contact with higher temperature grit may be avoided by better understanding of conditions at the cavity surface;
- Energy budget studies of the styroblock would provide better insight into the significance of evaporative cooling during periods of high surface temperature;

- Evaluation of the relationship between ambient and soil temperature in other environmental situations in order to establish regression equations that will allow the more accurate prediction of soil temperature in each situation.

The investigation has clearly shown the potential for heat damage to container-grown conifer seedlings during the succulent growth stage. Soil temperatures often approach lethal levels as they rise above that of their surroundings. Better understanding of this phenomenon would enable nursery managers to implement evasive controls while still favouring optimum seedling growth.

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APPENDIX I

TEMPERATURE MAXIMA

TRIAL 1

Maximum soil temperature reached:
Manitoba peat with vermiculite: 36.9°C 15:00 April 27

Longest run with mean (of 12 treatments) soil temperature >30°C:
45 minutes 15:00-15:45 April 27

Maximum ambient temperature reached:
27.6°C 17:00 April 29

Longest run with ambient temperature >25°C:
1 hour 15:15-16:15 April 29

TRIAL 2 - MAIN GREENHOUSE

Maximum soil temperature reached:
Manitoba peat with no additives: 44.4°C 16:00 June 12

Longest run with mean (of 8 treatments) soil temperature >40°C:
45 minutes 15:30-16:15 June 12

Maximum ambient temperature reached:
35.2°C 16:00 June 2

Longest run with ambient temperature >30°C:
5 hours 14:30-19:30 June 3

TRIAL 2 - HOOP GREENHOUSE

Maximum soil temperature reached:
Manitoba peat with no additives: 41.4°C 15:15 June 27

Longest run with mean (of 8 treatments) soil temperature >35°C:
3 hours 30 minutes 13:15-16:45 June 27

Maximum ambient temperature reached:
34.1°C 16:30 June 13

Longest run with ambient temperature >30°C:
4 hours 15 minutes 14:30-18:45 June 13

GRIT TRIAL

Granite Grit

Maximum soil temperature reached:
40.6°C 15:30 August 7

Longest run with mean (of 7 replications) soil temperature >40°C:
15 minutes 17:15-17:30 August 7

Forest Sand

Maximum soil temperature reached:
45.5°C 16:15 August 7

Longest run with mean (of 7 replications) soil temperature >40°C:
4 hours 14:30-18:30 August 7

Ambient Temperature

Maximum ambient temperature reached:
37.8°C 16:45 August 7

Longest run with ambient temperature >35°C:
3 hours 45 minutes 14:00-17:45 August 7

APPENDIX II

SOIL TEMPERATURE FREQUENCIES

TRIAL 1

Mean (of 12 treatments) soil temperature frequencies between 12:00-17:00 over Trial 1.

Class Interval (°C)	Frequency (%)	Cumulative Frequency (%)
17.5-22.5	27	27
22.5-27.5	49	76
27.5-32.5	24	100

TRIAL 2 - MAIN GREENHOUSE

Mean (of 8 treatments) soil temperature frequencies between 12:00-17:00 over Trial 2.

Class Interval (°C)	Frequency (%)	Cumulative Frequency (%)
12.5-17.5	0.35	0.35
17.5-22.5	23	23.35
22.5-27.5	22	45.35
27.5-32.5	23	68.35
32.5-37.5	25	93.35
37.5-42.5	6.65	100.00

TRIAL 2 - HOOP GREENHOUSE

Mean (of 8 treatments) soil temperature frequencies between 12:00-17:00 over Trial 2.

Class Interval (°C)	Frequency (%)	Cumulative Frequency (%)
12.5-17.5	5	5
17.5-22.5	19	24
22.5-27.5	35	59
27.5-32.5	23	82
32.5-37.5	16	98
37.5-42.5	2	100

GRIT TRIAL - FOREST SAND

Mean (of 7 replications) soil temperature frequencies between 12:00-17:00 over the Grit trial.

Class Interval (°C)	Frequency (%)	Cumulative Frequency (%)
27.5-32.5	19	19
32.5-37.5	48	67
37.5-42.5	33	33

GRIT TRIAL - GRANITE GRIT

Mean (of 7 replications) soil temperature frequencies between 12:00-17:00 over the Grit trial.

Class Interval (°C)	Frequency (%)	Cumulative Frequency (%)
27.5-32.5	48	48
32.5-37.5	52	100